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Title: DETERMINATION OF THE DUTY CYCLE OF WLAN FOR REALISTIC RADIO FREQUENCY ELECTROMAGNTIC FIELD EXPOSURE ASSESSMENT

Article Type: Review Article

Keywords: WLAN; Wi-Fi; radio frequency; duty cycle; exposure; electromagnetic

Corresponding Author: prof Wout Joseph, Ph.D.

Corresponding Author's Institution: Ghent University/IBBT

First Author: Wout Joseph, Ph.D.

Order of Authors: Wout Joseph, Ph.D.; Daan Pareit; Gunter Vermeeren; Dries Naudts; Leen Verloock; Luc Martens; Ingrid Moerman

Abstract: Wireless Local Area Networks (WLANs) are commonly deployed in various environments. The WLAN data packets are not transmitted continuously but often worst-case exposure of WLAN is assessed, assuming 100 % activity and leading to huge overestimations. Actual duty cycles of WLAN are thus of importance for time-averaging of exposure when checking compliance with international guidelines on limiting adverse health effects. In this paper, duty cycles of WLAN using Wi-Fi technology are determined for exposure assessment on large scale at 179 locations for different environments and activities (file transfer, video streaming, audio, surfing on the internet, etc.). The median duty cycle equals 1.4 % and the 95th percentile is 10.4 % (standard deviation SD = 6.4%). Largest duty cycles are observed in urban and industrial environments. For actual applications, the theoretical upper limit for the WLAN duty cycle is 69.8% and 94.7% for maximum and minimum physical data rate, respectively. For lower data rates, higher duty cycles will occur. Although counterintuitive at first sight, poor WLAN connections result in higher possible exposures. File transfer at maximum data rate results in median duty cycles of 47.6% (SD = 16%), while it results in median values of 91.5% (SD = 18%) at minimum data rate. Surfing and audio streaming are less intensively using the wireless medium and therefore have median duty cycles lower than 3.2% (SD = 0.5-7.5%). For a specific example, overestimations up to a factor 8 for electric fields occur, when considering 100 % activity compared to realistic duty cycles.

Response to Reviewers: Summary of the changes

October 5, 2012

Wout Joseph
Dept. of Information Technology
Ghent University/IBBT
Gaston Crommenlaan 8 box 201
B-9050 Ghent
BELGIUM

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Letter for reviewer 1

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Reviewer #1: This is a well written and interesting paper, reporting methods to calculate the duty cycle for WLAN transmitters under different real time scenarios. The data reported will be very useful in realistic assessment of the exposure of people to WLAN sources.

*Thank you for appreciating our paper.

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Response to Reviewer comment No. 1
* We found the article of Khalid et al very interesting and informative, but have a slightly different –and complementary– approach to the latter article. Khalid et al present elaborated exposure results for classroom scenarios in UK schools. In our article, one of the purposes is to find an upper limit for the duty cycle, based on the type of traffic that is used, which can then be applied to predict maximum duty cycles in different scenarios, depending on the application type and usage. We used indeed deliberately the duration of the considered activity as unit of time for the assessment of the duty cycles of actual applications (2 to about 6 minutes). For comparison with ICNIRP limits, we advise to use e.g., the mean duty cycles of Table 4 to have a realistic worst-case value. The reason is the following. If we would average a single 2-minute-activity over a 6 minute time frame (ICNIRP), we would obtain lower duty cycles, because no traffic is sent (except for e.g. some sporadic beacon control frames) during the remaining 4 minutes, which would decrease the obtained average value. But suppose that this 2-minute-activity is repeated several times for more than 6 minutes (e.g. successively watching different YouTube videos), we would obtain the average value we consider within this article. This is a "realistic worst-case" approach (as mentioned in the paper) assuming that the (successive) activities will take longer than 6 minutes (surfing on internet, skype, streaming at home, watching a movie). We prefer this realistic worst-case approach as one cannot know how long an activity takes: surfing, skype, watching a movie will take longer than 6 minutes, watching/streaming a trailer might be shorter. From our results one could try to determine "actual (on average)" duty cycles by multiplying the duty cycles we provide with usage patterns i.e., multiplying with the ratio of the average duration of an activity and 6 minutes (if the duration is longer than 6 minutes the ratio should be equal to 1). E.g., for a 2h-movie multiply by 1 as this takes longer than six minutes but watching a YouTube trailer of 2 minutes would be multiplying with a ratio of 2/6=1/3. But as one cannot know how long a time frame takes, we prefer this realistic worst-case approach, which can thus be an overestimation sometimes. Behaviour of children is even more difficult to determine but can then also to be characterized

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Your remark made us aware of the fact that there might be some confusion about the unit of time that is used. This has now been explained (we consider realistic worst-case) in Section 2.3 (when discussing the durations) and the usage patterns are mentioned as future research in the conclusions. The following text is added in Section 3.2:
"The unit of time in this paper is thus the duration of an activity. For comparison with ICNIRP limits, we advise to use the mean duty cycles of Table 4 to have a realistic worst-case value. This is a "realistic worst-case" approach assuming that the activities will take longer than 6 minutes, which is the ICNRIP time averaging requirement (surfing on internet, skype, streaming at home, watching a movie, successive activities). We prefer this realistic worst-case approach as one cannot know how long an activity in reality lasts: surfing, skype, watching a movie will take longer than 6 minutes but watching/streaming a trailer might be shorter."

*In the conclusions we added the following:
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2- The authors mention that one can use the duty cycles reported in this paper for realistic exposure estimation when activities of people are known well, for example exposure of children during video streaming in a class. Given that the authors only calculate the duty cycle during the actual file transfer (unit of time here), what happens if 30 children do this activity all together? how would the authors estimate the cumulative exposure when the averaging time is not sufficiently long?

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*For the effect of multiple users: in Section 3.2 we mention that we assume no other clients are present. When there are multiple clients that have separate data transfers (thus no multicasting of the video stream), these different data streams will have to be sent over the wireless network. As you know, Wi-Fi clients cannot send simultaneously but will send intermittently (after contenting with each other for wireless medium access). Thus, the duty cycle will gradually increase with multiple clients until the maximum duty cycle (as indicated in the article) is reached. However, in this case there are at least two factors which will cause the duty cycle not to increase linearly and which cause the maximum achieved duty cycle for a group of clients to be lower compared to the case when only one client would be heavily using the wireless medium at its maximum. The first one is that a single client results in a minimum back-off time B, but for multiple clients, a higher back-off time will be present. This results in more idle periods and thus in lower duty cycles. The second reason is that the client data transfers will also throttle back when using the TCP transport layer (which is still mostly used for reliable data transfers). This way, we can again state that the presented maximum duty cycles for a single user are a realistic worst-case value, which is even more pessimistic for a higher amount of clients.
For the duration of the averaging time: For shorter durations than 6 minutes the usage patterns from the remark above can again be used.
For the cumulative exposure: one performs a measurement of the total Wi-Fi exposure using max-hold (huge overestimation), which is a cumulative value from the different clients (children using the laptop). Next, by multiplying with the duty cycles that are presented in this article, one thus obtains a realistic worst-case value prediction.

Most scenarios will have nowadays one single concurrent user at a hotspot, for use at house etc. (information of mobile operators, networks are currently designed in this way). The duty cycles we provided can then be applied. However there are exceptions like the class room example with children using a wireless application and in future increasing use may change this statement. Therefore the following procedure to assess (cumulative exposure) is proposed, this is also now included in Section 2.3:

<here equation (3) from paper>

Firstly, one performs a measurement of the total Wi-Fi exposure using max-hold setting of the SA (huge overestimation: 100% duty cycle), which is a cumulative value if more than one client is present. Secondly, one can select the duty cycles from Table 4 for the application used. Finally, by multiplying with the duty cycles, one thus obtains a realistic worst-case value prediction for single user and single application.
If multiple clients are present, one can estimate the resulting duty cycle as the duty cycle of one client times number of clients, with as theoretical maximum the values of Table 3:

(3)
Where Dmultiple clients, D, n, and Dmax represent the duty cycle with n clients, D the duty cycle for a single client, n the number of clients and Dmax the upper limits of Table 3. However, the upper limits of Table 3 will be an overestimation due to the following reasons. The first one is that a single client results in a minimum back-off time B, but for multiple clients, a higher back-off time will be present. This results in more idle periods and thus in lower duty cycles. The second reason is that the client data transfers will also throttle back when using the TCP transport layer (which is still mostly used for reliable data transfers). This way, we can again state that the presented maximum duty cycles are a realistic worst-case value, which is even more pessimistic for a higher amount of clients. Calculations show that for maximal occupation the duty cycles from Table 3 namely 70-94% (CW = 15, single user) reduce to 5.5-31.3% (CW = 1023, a lot of users) for 54 – 6 Mbps, respectively. So our results are realistic worst-case values. We advise not to apply the numbers for maximal occupation, as these can be an underestimation when multiple users are present but maximal occupation is not reached.
Also for different parallel applications, the same reasoning can be used and the resulting duty cycle will be the sum of the duty cycles of the individual applications with as maximal values the upper limits of Table 3.

*We added this now in the text in Section 2.3, in the new subsection 2.3.2 (Procedure to estimate exposure using duty cycle).

3- The authors rightly argue that poor WLAN connections result in higher possible exposure. They also suggest that since positions with bad connections are located far from the access point, it results in lower received powers and lower exposure due to higher distance. My question to the authors is what will be the exposure of a person that stands next to the access point? surely he/she would not be exposed as low as someone in a longer distance. I think the authors need to explain this slightly further in the text.

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*The sentence "Note however that positions with bad connections are located far from the access point, resulting also in lower received powers and lower exposures (higher distances)" might confuse the reader. The sentence is written from the view point of the user of a PC or laptop who is at a large distance of the access point and having a poor wireless connection. This user will be exposed to low levels of EMF. Of course, when looking at exposure, also persons who are not using the network will be exposed. These persons can be at any distance from the access point. In general, poor connections have low data rates resulting in larger duty cycles and thus an increased exposure at all distance from the access point. In conclusion, the influence of the duty cycle on the exposure is independent of the distance.
To avoid confusion, we have removed the mentioned sentence from the text and modified the text as follows:

"…, it means that a poor connection (which only deliver low data rates) between an access point and a user result in higher possible exposure all around the access point."

4- Can the authors explain a bit more in details, that how the duty cycle was calculated with spectrum analyser in zero span?

Response to Reviewer comment No. 4
*This is done as follows:

For the determination of the duty cycle D (%), the zero span mode of the SA for the different active channels with center frequency equal to the channel frequency (2412 MHz + 5•k MHz, k = 0, …,12) is used with the settings shown in Table 1. To obtain these settings, experiments with the D-Link AP in idle mode and the WiLab AP in broadcast mode were performed. We estimate then D from tactive in (1) equal to the time that a measured packet is 5 dB above the noise floor (equal to 78 dBm for the settings in Table 1). This is shown in Figure 1 in Verloock et al. 2010, where tactive and ttot are experimentally determined using the zero span mode.

*We take different single sweeps and chose the following settings for the estimation of D: the root-mean-square (RMS) detector, a sweep time (SWT) of 1 ms and a resolution bandwidth (RBW) of 1 MHz.
Due to the stochastic signal characteristics of the WLAN signals an RMS detector must be used in order to avoid systematic overestimation of the fields (as in case of using a peak detector).
The SWT has to be sufficiently large to measure as many packets as possible in a single sweep but not too large in order to distinguish between individual packets. When SWT is too large, packets cannot be distinguished anymore, if SWT is too small then too many traces are needed to obtain an accurate estimate of D. As a compromise we chose SWT equal to 1 ms.
RBW has to be large enough to have smaller variations of the noise floor (variations less for 1 MHz than e.g., for 300 kHz) and to obtain a signal that is high enough above the noise floor to be able to detect it. RBW has to be small enough to avoid large contributions of adjacent channels, which can result in a bad estimation of T. We chose thus RBW equal to 1 MHz.
The number of single sweeps required to obtain an accurate estimate of T is equal to 2,200. This number is determined by performing 100,000 single sweeps and reducing this number until a deviation lower than 5 % (with respect to 100,000 sweeps) is obtained. This number is just an optimal number to reduce the measurement time.
*We added part of the first paragraph of this explanation in Section 2.1

5- Finally, does the air magnet provide the duty cycle without further processing assumptions?

Response to Reviewer comment No. 5
*The AirMagnet has a resolution bandwidth of 156.3 kHz and a sweep time of 64 ms for 20 MHz. No further processing is applied manually or automatically afterwards.

FACULTEIT INGENIEURSWETENSCHAPPEN

To editor Progress in Biophysics and Molecular Biology

October 5, 2012

Wout Joseph
Dept. of Information Technology
Ghent University/IBBT
Gaston Crommenlaan 8, box 201
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BELGIUM

Dear Editor:

Please find enclosed our revised manuscript "DETERMINATION OF THE DUTY CYCLE OF WLAN FOR REALISTIC RADIO FREQUENCY ELECTROMAGNTIC FIELD EXPOSURE ASSESSMENT" which we would like to publish in your journal Biophysics and Molecular Biology.

We have included the document "Response to reviewers" at the end of the revised manuscript. This is a detailed summary of the changes made in preparing the revised manuscript.

Exposure to radio frequency electromagnetic fields has been increasing in the last few years, but only limited data on personal exposure levels are available about wireless local area networks (WLAN). Actual duty cycles of WLAN are of importance for time-averaging of exposure when checking compliance with international guidelines (e.g., ICNRIP) on limiting adverse health effects. In our paper, duty cycles of WLANs using Wi-Fi technology are determined experimentally for exposimetry of these sources. Future studies can use the results of this paper to obtain realistic WLAN exposures and relate possible health effects to exposure values.
Recently two articles about the radio frequency exposure topic are published in your journal (Khalid et a. 2011 and Juhasz et al. 2011) and we think our publication is also suitable for your journal.

Moreover we want to state the following aspects concerning this research article:

- The manuscript is an original work and has not been previously published, and is not under consideration for publication elsewhere.
- No animals or humans are used in this research
- We give permission to the publisher (Biophysics and Molecular Biology) to reproduce figures, tables, questionnaires, or a substantial block of text.
- All authors have read the manuscript, agree that the work is ready for submission to a journal, and accept responsibility for the manuscript's contents.
- This submission contains 4 tables and 4 figures.

Yours sincerely,

Prof. Wout Joseph, Ph. D.
Ghent University/IBBT
Gaston Crommenlaan 8 box 201
B-9050 Gent
BELGIUM
email:wout.joseph@intec.UGent.be
tel: +32 9 33 14918
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Summary of the changes

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$$D_{multipleclients} = \begin{cases} D \times n, if \ D \times n \leq D_{\max} \\ D_{\max}, if \ D \times n > D_{\max} \end{cases} \tag{3}$$

Where $D_{multiple\ clients}$, D, n, and D_{max} represent the duty cycle with n clients, D the duty cycle for a single client, n the number of clients and D_{max} the upper limits of Table 3. However, the upper limits of Table 3 will be an overestimation due to the following reasons. The first one is that a single client results in a minimum back-off time B, but for multiple clients, a higher back-off time will be present. This results in more idle periods and thus in lower duty cycles. The second reason is that the client data transfers will also throttle back when using the TCP transport layer (which is still mostly used for reliable data transfers). This way, we can again state that the presented maximum duty cycles are a realistic worst-case value, which is even more pessimistic for a higher amount of clients. Calculations show that for maximal occupation the duty cycles from Table 3 namely 70-94% (CW = 15, single user) reduce to 5.5-31.3% (CW = 1023, a lot of users) for 54 – 6 Mbps, respectively. So our results are realistic worst-case values. We advise not to apply the numbers for maximal occupation, as these can be an underestimation when multiple users are present but maximal occupation is not reached.
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For the determination of the duty cycle D (%), the zero span mode of the SA for the different active channels with center frequency equal to the channel frequency (2412 MHz + 5·k MHz, k = 0, …,12) is used with the settings shown in Table 1. To obtain these settings, experiments with the D-Link AP in idle mode and the WiLab AP in broadcast mode were performed. We estimate then D from t_{active} in (1) equal to the time that a measured packet is 5 dB above the noise floor (equal to -78 dBm for the settings in Table 1). This is shown in Figure 1 in Verloock et al. 2010, where t_{active} and t_{tot} are experimentally determined using the zero span mode.

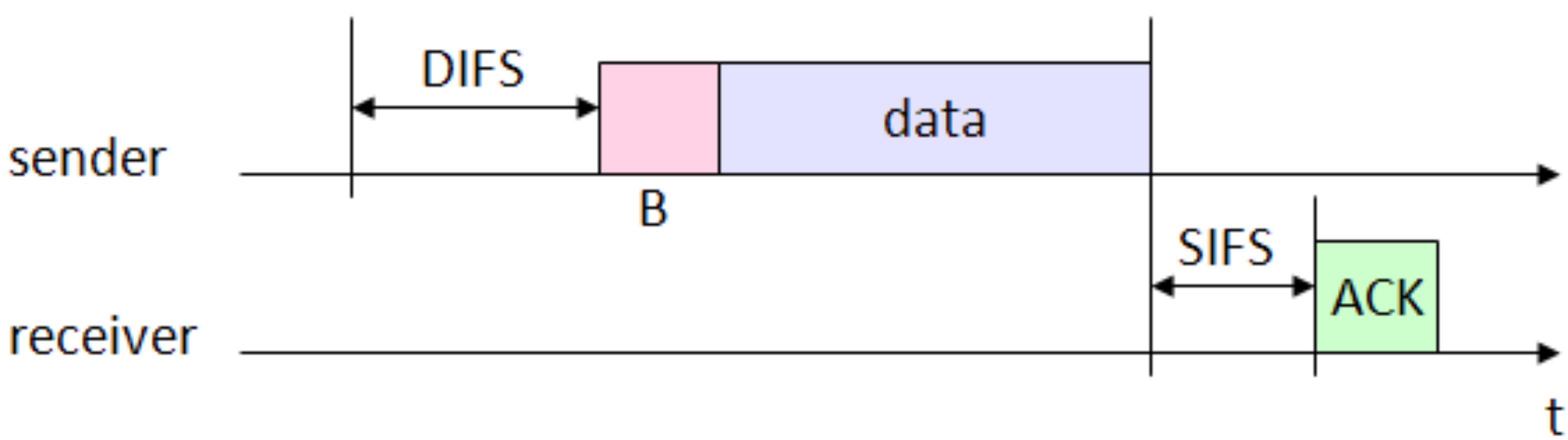
*We take different single sweeps and chose the following settings for the estimation of D: the root-mean-square (RMS) detector, a sweep time (SWT) of 1 ms and a resolution bandwidth (RBW) of 1 MHz.
Due to the stochastic signal characteristics of the WLAN signals an *RMS detector* must be used in order to avoid systematic overestimation of the fields (as in case of using a peak detector).

The *SWT* has to be sufficiently large to measure as many packets as possible in a single sweep but not too large in order to distinguish between individual packets. When SWT is too large, packets cannot be distinguished anymore, if SWT is too small then too many traces are needed to obtain an accurate estimate of *D*. As a compromise we chose SWT equal to 1 ms.
RBW has to be large enough to have smaller variations of the noise floor (variations less for 1 MHz than e.g., for 300 kHz) and to obtain a signal that is high enough above the noise floor to be able to detect it. RBW has to be small enough to avoid large contributions of adjacent channels, which can result in a bad estimation of *T*. We chose thus RBW equal to 1 MHz.
The *number of single sweeps* required to obtain an accurate estimate of *T* is equal to 2,200. This number is determined by performing 100,000 single sweeps and reducing this number until a deviation lower than 5 % (with respect to 100,000 sweeps) is obtained. This number is just an optimal number to reduce the measurement time.
*We added part of the first paragraph of this explanation in Section 2.1

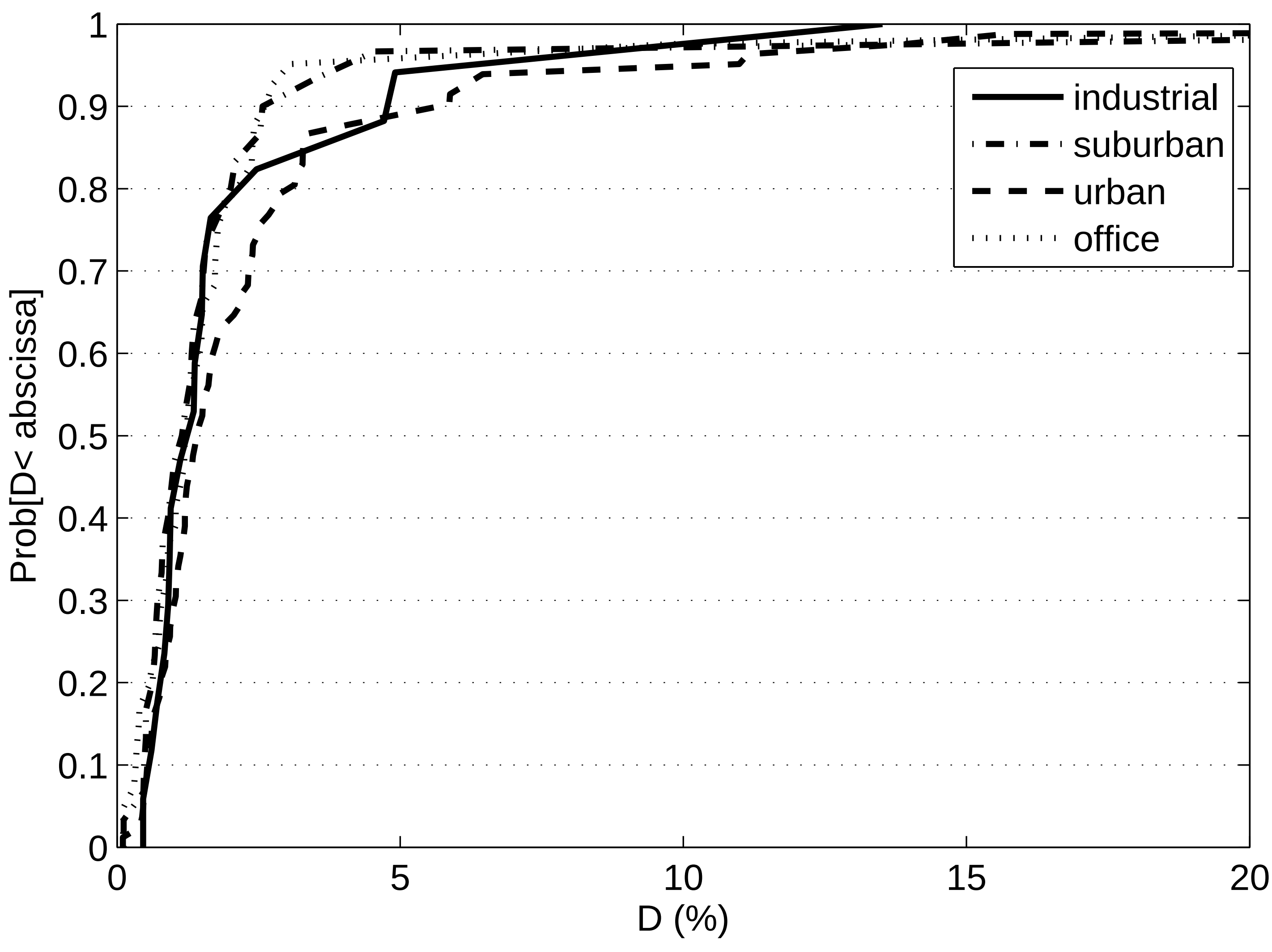
5- Finally, does the air magnet provide the duty cycle without further processing assumptions?

Response to Reviewer comment No. 5
*The AirMagnet has a resolution bandwidth of 156.3 kHz and a sweep time of 64 ms for 20 MHz. No further processing is applied manually or automatically afterwards.

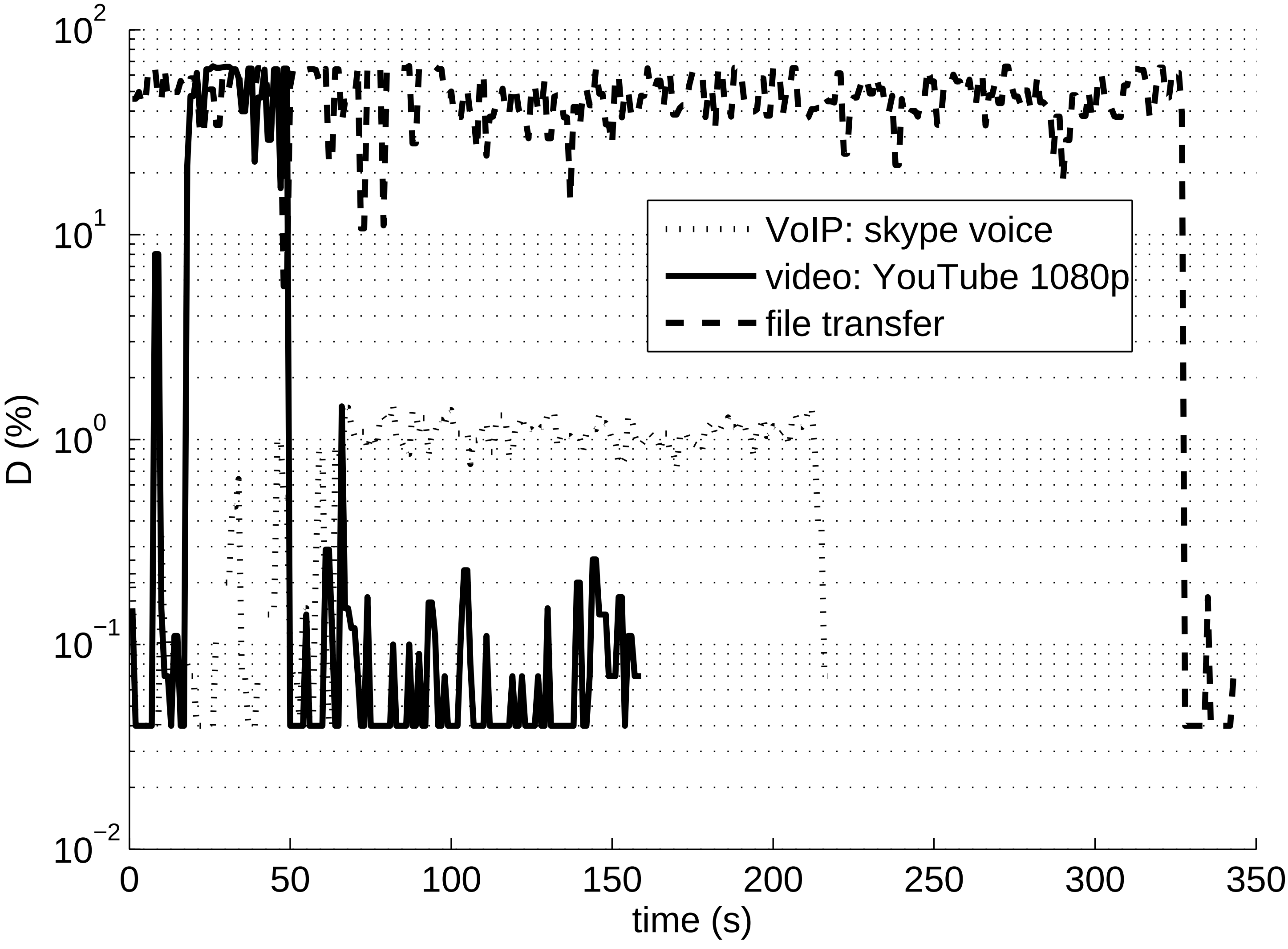
Figure



Figure

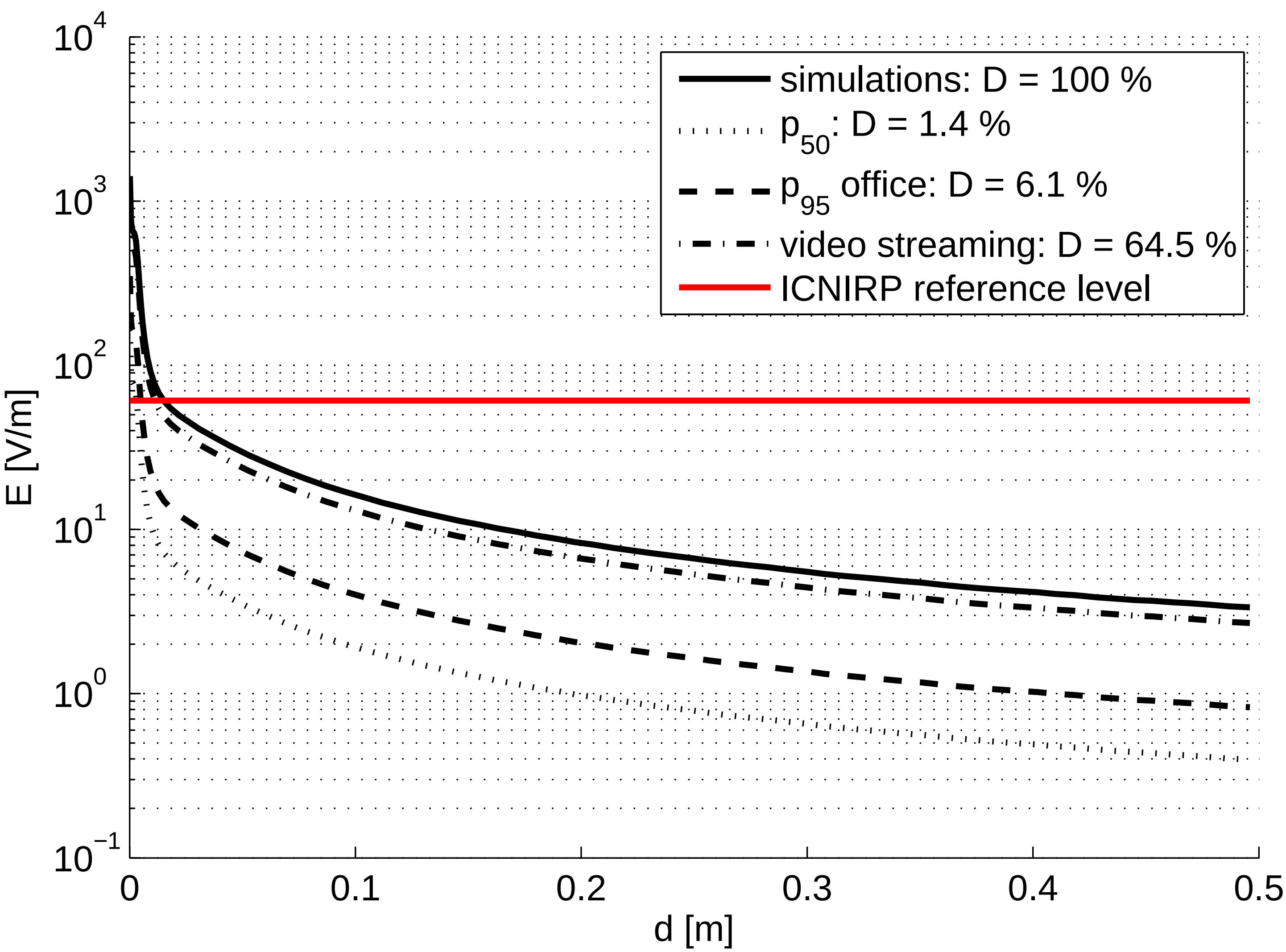

industrial
suburban
urban
office
Prob[D< abscissa]
D (%)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20

Figure



10^2
10^1
10^0
10^{-1}
10^{-2}
D (%)
0
50
100
150
200
250
300
350
time (s)
VoIP: skype voice
video: YouTube 1080p
file transfer

Figure



simulations: D = 100 %
p50: D = 1.4 %
p95 office: D = 6.1 %
video streaming: D = 64.5 %
ICNIRP reference level
E [V/m]
d [m]
10^4
10^3
10^2
10^1
10^0
10^−1
0
0.1
0.2
0.3
0.4
0.5

DETERMINATION OF THE DUTY CYCLE OF WLAN FOR REALISTIC RADIO FREQUENCY ELECTROMAGNTIC FIELD EXPOSURE ASSESSMENT

Wout Joseph[1], Daan Pareit[1], Günter Vermeeren[1], Dries Naudts[1], Leen Verloock[1], Luc Martens[1], Ingrid Moerman[1]

[1]**Department of Information Technology, Ghent University / IBBT Gaston Crommenlaan 8, B-9050 Ghent, Belgium,**

Corresponding author:
Prof. Wout Joseph, Ph. D.
Ghent University/IBBT
Gaston Crommenlaan 8 box 201
B-9050 Gent
BELGIUM
email:wout.joseph@intec.UGent.be
tel: +32 9 33 14918
fax: +32 9 33 14899

Key Words- **WLAN; Wi-Fi; radio frequency; duty cycle; exposure; measurement; RF-EMF; electromagnetic; compliance; general public; health risk; ICNIRP**

abbreviations

EMF: electromagnetic field
ICNIRP: International Commission on Non-ionizing Radiation Protection
IEEE: Institute of Electrical and Electronics Engineers
RF: radio frequency
RF-EMF: radio frequency electromagnetic field
OFDM: Orthogonal Frequency Division Multiplexing
RMS: root-mean-square
WLAN: wireless local area network

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2. There are no potential conflicts of interest related to this work.

3. The work described is original and has not been published previously, it is not under consideration for publication elsewhere, the publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and if accepted, it will not be published elsewhere including electronically in the same form, in English or in any other language, without the written consent of the copyright-holder.

Abstract-

Wireless Local Area Networks (WLANs) are commonly deployed in various environments. The WLAN data packets are not transmitted continuously but often worst-case exposure of WLAN is assessed, assuming 100 % activity and leading to huge overestimations. Actual duty cycles of WLAN are thus of importance for time-averaging of exposure when checking compliance with international guidelines on limiting adverse health effects. In this paper, duty cycles of WLAN using Wi-Fi technology are determined for exposure assessment on large scale at 179 locations for different environments and activities (file transfer, video streaming, audio, surfing on the internet, etc.). The median duty cycle equals 1.4 % and the 95th percentile is 10.4 % (standard deviation SD = 6.4%). Largest duty cycles are observed in urban and industrial environments. For actual applications, the theoretical upper limit for the WLAN duty cycle is 69.8% and 94.7% for maximum and minimum physical data rate, respectively. For *lower* data rates, *higher* duty cycles will occur. Although counterintuitive at first sight, poor WLAN connections result in higher possible exposures. File transfer at maximum data rate results in median duty cycles of 47.6% (SD = 16%), while it results in median values of 91.5% (SD = 18%) at minimum data rate. Surfing and audio streaming are less intensively using the wireless medium and therefore have median duty cycles lower than 3.2% (SD = 0.5-7.5%). For a specific example, overestimations up to a factor 8 for electric fields occur, when considering 100 % activity compared to realistic duty cycles.

1 INTRODUCTION

Nowadays, Wireless Local Area Networks (WLANs) using Wi-Fi® technology are commonly deployed in various environments such as office buildings and at home. As a consequence, many people are exposed to the electromagnetic fields irradiated by these networks during long periods of time. Exposure assessment of WLAN is only rarely investigated (Foster 2007, Juhász et al. 2011, Khalid et al. 2011, Kuhn 2007, Peyman et al. 2011, Schmid et al. 2007, Verloock et al. 2010). These studies proposed procedures to assess WLAN exposure to test compliance with safety standards and guidelines such as the International Commission on Non-ionizing Radiation Protection (ICNIRP) (ICNIRP 1998), Institute of Electrical and Electronics Engineers (IEEE) (IEEE C95.1 2005), Federal Communications Commission (FCC) (FCC 2001), and European Council Recommendation (ERC) (ERC 1999) and provide typical exposure values.

WLAN data packets are transmitted in bursts and not continuously. According to international guidelines, the exposure is to be averaged over 6 min or 30 min time period (ICNIRP 1998, IEEE C95.1 2005). Hence, the correct assessment of the exposure requires the knowledge of the duty-cycle. But often worst-case exposure of WLAN is assessed, assuming 100 % activity: e.g., in Verloock et al. (2010), a procedure to assess WLAN exposure is proposed using the maximum-hold mode of the spectrum analyser (SA) (i.e., retaining the maximal values). It is possible to assess the duty cycle but this needs specialized equipment and is a time-consuming and complex procedure (Joseph et al. 2002, Verloock et al. 2010). The worst-case approaches lead to huge overestimations of the actual WLAN exposure. Therefore, the objective of this paper is to assess WLAN duty cycles on large scale for different environments and different activities and to provide distributions of the WLAN duty cycle. To our knowledge this has only been investigated in a recent article (Khalid et al. 2011), where the analysis was limited to schools. In this paper, the WLAN duty cycle for Wi-Fi technology is assessed the first time in real circumstances using an in-situ setup for various environments. Moreover, duty cycles are determined experimentally for various specific activities such as voice over IP (VoIP), file transfer, video streaming, audio, surfing on the internet, etc. These duty cycles can then be used for estimation and assessment of *realistic* WLAN exposure. Here, the duty cycle is measured at a total of 179 locations in Belgium and the Netherlands, for five different environments. Finally, as an application, a simulation to calculate the field strength for WLAN exposure with actual duty cycles is provided. The results of this paper will enable simple and realistic WLAN exposure assessment by application of the provided duty cycles.

2 MATERIALS AND METHODS

2.1 METHOD TO ASSESS WLAN DUTY CYCLES IN-SITU

We define the duty cycle D (%) as the ratio of active duration t_{active} (s) to total duration t_{tot} (s) of the WLAN signal (Verloock et al. 2010):

$$D = 100 \cdot \frac{t_{active}}{t_{tot}} \ (\%) \tag{1}$$

For an in-situ assessment of the exposure to radio-frequency electromagnetic fields, the spectrum analyser often measures in maximum-hold (max-hold) mode until the signal stabilizes. In this way the maximum field level during the measurement time is determined. In a WLAN, data is not transmitted continuously. Thus, the maximum field level measured with a spectrum analyser (SA) in max-hold mode overestimates largely the time-averaged field level. Because these WLAN signals are not continuously transmitted, the maximal value has to be multiplied with a duty cycle to obtain an accurate estimation of the total root-mean-square (RMS) power density averaged over 6 minutes as proposed by ICNIRP 1998, or 30 minutes as proposed by IEEE C95.1 2005.

The following method to assess correctly Wi-Fi exposure is used (Joseph et al. 2012, Verloock et al. 2010): firstly, the active WLAN channels (i.e., channels on which Wi-Fi activity is measured) are determined with a WLAN-packet analyzer. Secondly, a maximum-hold measurement of the electric field of the different channels is performed using a tri-axial measurement probe connected to the SA. Thirdly, the duty cycle of the active channels is determined. The duty cycle of the active channels is measured using a SA in zero span with appropriate settings of the SA (Verloock et al. 2010). These settings are listed in Table 1 and validated in Verloock et al. (2010). We estimate D from t_{active} of a WLAN signal as the time that a measured packet is 5 dB above the noise floor. This is shown in Figure 1 in Verloock et al. (2010), where t_{active} and t_{tot} are experimentally determined using the zero span mode.

Finally, the total averaged field is determined from the duty cycle and the max-hold field strength as follows:

$$E_{tot}^{avg} = \sqrt{D} \cdot E_{tot}^{\max-hold} \quad (V/m) \tag{2}$$

with D the duty cycle, E_{tot}^{avg} the total average (over 6 min, 30 min) electric-field strength due to WLAN, and $E_{tot}^{\max-hold}$ the max-hold electric field strength (assuming continuously present).

2.2 Investigated configurations and measurement equipment

2.2.1 Equipment

Using a Wi-Fi-packet analyzer, the active Wi-Fi channels are determined. The analyzer consists of the software tool Airmagnet (Airmagnet 2011) together with a laptop and a Wi-Fi card (type Proxim ORiNOCO 11 a/b/g Client Combocard gold). For all in-situ environments, we only consider the 2.4 GHz band where Wi-Fi networks are present using IEEE 802.11b and IEEE 802.11g technology (IEEE 802.11b 1999, 802.11g 1999). So-called “802.11b networks” use a physical air interface, which is based on CDMA (Code Division Multiple Access) while so-called "802.11g networks" use a physical air interface, which is based on OFDM (Orthogonal Frequency Division Multiplexing). They were originally defined in IEEE Std 802.11b-1999 and IEEE Std 802.11g-2003, respectively, but both standard documents are currently obsoleted by the revised standard document IEEE Std 802.11-2012, which still includes these physical air interfaces. However, the "802.11b" and "802.11g" naming is still used for these networks.

The SA-measurement setup of the narrowband measurements consists of tri-axial Isotropic Antennas (type Rohde and Schwarz TS-EMF, dynamic range of 1 mV/m – 100 V/m for the frequency range of 80 MHz – 3 GHz) in combination with a spectrum analyser (type Rohde and Schwarz FSL6, frequency range of 9 kHz – 6 GHz). The measurement uncertainty for the electric field is ± 3 dB for the considered setup (CENELEC 2008). This uncertainty represents the expanded uncertainty evaluated using a confidence interval of 95 %.

2.2.2 Configurations

The WLAN duty cycle is measured with the SA using the procedure of above at a total of 179 locations in two countries, namely, Belgium and the Netherlands. At all these locations, the duty cycle could be assessed as WLAN was significantly present (in total 344 locations are considered and at 179 WLAN was measured). The considered environments are the following: rural, residential, urban, suburban, office, and industrial environments (Joseph et al. 2012, Verloock et al. 2010). Both indoor and outdoor locations are considered. Table 2 summarizes the environments and the number of locations per environment where WLAN was measured.

2.3 DUTY CYCLE FOR TYPICAL APPLICATIONS IN A LAB ASSESSMENT

2.3.1 Theory and method

One can also assess exposure during typical activities or using different applications (VoIP, file transfer, video streaming, audio, surfing on the internet, etc.). Thus, if one knows the application one is using on Wi-Fi, the exposure can be assessed using the provided duty cycles. To this end, we use IEEE 802.11a technology. A so-called “802.11a network” uses a physical interface which is also based on OFDM, just like IEEE 802.11g. It was originally defined in document IEEE Std 802.11a-1999, but it is now also included in the latest IEEE Std 802.11-2012. For our lab assessment, we use a 802.11a network instead of a 802.11g network as the former is deployed at 5 GHz instead of 2.4 GHz for the latter. As the 5 GHz band is less used than the 2.4 GHz, we are less susceptible to interference for our measurements. We determine the duty cycles of the different applications as follows for 802.11a (IEEE 802.11a 1999).

Firstly, we calculate theoretically an upper limit for the duty cycle *D*. Figure 1 shows how data is transmitted using Wi-Fi. To transmit data from a client to an access point (AP), there is a waiting time DIFS (Distributed Inter-Frame Space) and a random backoff time B (to avoid that multiple users would access the wireless medium simultaneously). Then the data is transmitted (typically 1500 bytes is the maximal value for an Internet Protocol (IP) packet). Next, there is a waiting time SIFS (Short Interframe Space) and finally, the AP sends an acknowledgement ACK (see Figure 1). We neglect transmission times as they are very small (e.g. 0.33 μs for 100 m). We further assume that no re-transmissions are needed, no other clients are present and the highest modulation and coding scheme (64-QAM 3/4) is used, resulting in a maximum physical data rate of 54 Mbps (IEEE 802.11g 1999). We use a minimum contention window (CW) of 15 time slots. This means that the random back-off time B will be chosen between 0 and 15 time slots, which results in an average of 67.5 μs. The minimum CW value is selected here to reflect a realistic worst-case exposure estimation. This CW value will typically be applicable for a single or very few users who are connected to the same access point. The duration of the aforementioned transmissions are 34 (DIFS), 67.5 (average for B), 248 (data), 16 (SIFS) en 24 μs (ACK), respectively. This results in a netto data rate of (1500 bytes·8 bits/byte)/(34+67.5+248+16+24 μs) = 30.8 Mbps. Optimally, the medium is thus occupied during 248+24 μs (data and ACK). The other 34+67.5+16 μs are thus idle waiting time durations, where nothing happens. Thus, when the client is transmitting 1500 bytes continuously, the duty cycle or percentage of active time is only (248+24)/(248+24+34+67.5+16) = 69.83%. This is thus a theoretical upper limit for the actual WLAN duty cycle when the *highest* modulation and coding scheme is used and the highest data rate is achieved.

When WLAN signal quality is getting poor, lower modulations will be used to still maintain a stable connection, at the expense of a lower physical data rate. But for lower modulations (and thus lower physical data rates) higher duty cycles will be obtained because the time to transmit data and control packets will be higher (e.g. 248+24 μs for 54 Mbps becomes 2072+44 μs for 6 Mbps), while the idle durations remain the same. For other data rates the duty cycle can be calculated analogously. Table 3 summarizes the maximum duty cycles for the various data rates of 802.11a. Highest theoretical duty cycles are thus obtained for 6 Mbps (lowest modulation and data rate for 802.11a and thus the worst-quality connection) and equal to 94.7%. Thus the worse the connection (when only low physical data rates are possible), the higher the duty cycle and the resulting exposure can be. Although it might appear counterintuitive at first sight, it means that a poor connection (which only deliver low data rates) between an access point and a user result in higher possible exposure all around the access point. For completeness, also the duty cycles are calculated and provided in Table 3 for each data rate of 802.11g for the minimum CW value.

For actual applications, the duty cycle will be even lower than the theoretical maxima of 69.83% (54 Mbps) and 94.7% (6 Mbps), as data is not always continuously transmitted. The duty cycle for real activities will be measured here for the highest (54 Mbps) and lowest (6 Mbps) data rate in an IEEE 802.11a network. The following activities are here considered: (i) surfing to a news site (BBC 2012) on the internet (ii) Voice over IP (VoIP) using Skype (Skype 2012), (iii) video call using Skype, (iv) audio streaming using Spotify (Spotify 2012), (v) normal video streaming using YouTube (360p, Youtube 2012), (vi) High Definition video streaming using YouTube (1080p, same video), and (vii) file transfer (download of a large file from Ubuntu 2012). The video streaming "360p" means that the video screen is 360 pixels wide (normal video watching), while "1080p" corresponds with high definition video, characterized by 1080 horizontal lines of vertical resolution and noninterlaced scanning (progressive scan).

To assess the duty cycle *D* of these activities the Airmagnet Wi-Fi packet analyzer, described in Section 2.2.1, measures the instantaneous duty cycle in % for different activities over an 802.11a Wi-Fi connection between two computers in the 5 GHz band (channel 48, frequency 5240 MHz, no detected activity on neighbouring channels during the measurement). For the access point, we use a ZOTAC NM10-A-E mini-pc with a Sparklan wireless interface card type WPEA-110N/E/11n, using a mini PCIe 2T2R chipset AR9280, and an omnidirectional dipole antenna. The mini-pc has an Atom D525 2x1.8 GHz CPU and a RAM memory of 4GB 800MHz DDR2 and is running Ubuntu Linux 12.04. For the client, we use a Dell Latitude E6400 laptop with an EMEA Intel Centrino Ultimate-N 6300 wireless interface card with two onboard antennas. The laptop uses an Intel Core I7-2720QM quad-core 2.2 GHz CPU with a RAM memory of 8 GB 1.333 MHz DDR3 and is running Windows 7 Enterprise. The computers are placed line of sight (LOS) at a distance of 0.5 m, resulting in an optimal connection quality at the maximum physical data rate of 54 Mbps. For measurements at 6 Mbps, we limited the software of the access point to only support this data rate, while keeping all equipment at the same place. These measurements are performed with 802.11a at 5 GHz to avoid interference with existing 802.11g Wi-Fi networks at 2.4 GHz. The duty cycles measured for the activities over 802.11a (IEEE 802.11a 1999) are also comparable for 802.11g as they share the same principles and protocols for the physical air interface with slightly different parameter sets. Samples are acquired each second over at least 120 s (or more, up to 350 s) until the video or audio fragment is finished or the file is transferred. The duration of this measurement can differ due to the use of actual activities on actual sites (YouTube, Skype, Spotify). The unit of time in this paper is thus the duration of an activity. For comparison with ICNIRP limits, we advise to use the mean duty cycles of Table 4 to have a realistic worst-case value. This is a "realistic worst-case" approach assuming that the activities will take longer than 6 minutes, which is the ICNRIP time averaging requirement (surfing on internet, skype, streaming at home, watching a movie). We prefer this realistic worst-case approach as one cannot know how long an activity in reality lasts: surfing, skype, watching a movie will take longer than 6 minutes but watching/streaming a trailer might be shorter.

2.3.2 Procedure to estimate exposure using duty cycle

Firstly, one performs a measurement of the total Wi-Fi exposure using max-hold setting of the SA (huge overestimation: 100% duty cycle), which is a cumulative value if more than one client is present. Secondly, one can select the duty cycles from Table 4 for the application used. Finally, by multiplying with the duty cycles, one thus obtains a realistic worst-case value prediction *for single user and single application*.

If multiple clients are present, one can estimate the resulting duty cycle as the duty cycle of one client times number of clients, with as theoretical maximum the values of Table 3:

$$D_{multipleclients} = \begin{cases} D \times n, if \; D \times n \leq D_{\max} \\ D_{\max}, if \; D \times n > D_{\max} \end{cases} \qquad (3)$$

Where $D_{multiple\ clients}$, D, n, and D_{max} represent the duty cycle with n clients, D the duty cycle for a single client, n the number of clients and D_{max} the upper limits of Table 3. However, the upper limits of Table 3 will be an overestimation due to the following reasons. The first one is that a single client results in a minimum back-off time B, but for multiple clients, a higher back-off time will be present. This results in more idle periods and thus in lower duty cycles. The second reason is that the client data transfers will also throttle back when using the TCP transport layer (which is still mostly used for reliable data transfers). This way, we can again state that the presented maximum duty cycles are a realistic worst-case value, which is even more pessimistic for a higher amount of clients. Calculations show that for maximal occupation the duty cycles from Table 3 namely 69.8-94.7% (CW = 15, single user) reduce to 5.5-31.3% (CW = 1023, a lot of users) for 54 – 6 Mbps, respectively. So our results are realistic worst-case values. We advise not to apply the numbers for maximal occupation, as these can be an underestimation when multiple users are present but maximal occupation is not reached.

Also for different parallel applications, the same reasoning can be used and the resulting duty cycle will be the sum of the duty cycles of the individual applications with as maximal values the upper limits of Table 3.

3 RESULTS AND DISCUSSION

3.1 GENERAL RESULTS AND RESULTS PER ENVIRONMENT

Table 2 lists the overall duty cycle measured during the large measurement campaign performed in Belgium and the Netherlands ("All environments"). The median or 50th percentile (p_{50}) equals 1.4 % (average exposure) and the 95th percentile is 10.4 % (realistic worst-case exposure). It is clear that the worst-case approaches assuming continuous WLAN exposure (thus D = 100 %) result in large overestimations.

The results per environment are summarized in Table 2 and Figure 2, which shows the different cumulative distribution functions (cdf) for *D* for industrial, urban, suburban, and office environments. Largest duty cycles D are observed in urban and industrial environments with 95th percentiles of about 11 %. The median duty-cycles are similar for the different environments and vary from 1.2 to 1.9 %. Standard deviations (SD) vary from 3.1 to 7.1%. These values correspond in order of magnitude with the duty cycles of the access points in Khalid et al. (2011), which are measured in 7 networks in schools and ranged from 1.0% to 11.7% with a mean of 4.79%. The mean value of *D* in Khalid et al. (2011) is higher because networks in schools are considered during lessons thus during activity (overall median of 1.4% versus 4.8% in Khalid et al. (2011)). In our study, duty cycles in actual circumstances are measured without knowledge of activity in the different environments. Therefore, also periods of less activity are included in our data resulting in lower duty cycles than in Khalid et al. (2011). The standard deviation was 3.8% in Khalid et al. (2011), which is within the range of our standard deviations (3.1-7.1%). We advise to always include the measurement of the duty cycle in exposure measurements using e.g., the method of Verloock et al. (2010). For numerical investigations or when the duty cycle cannot be assessed experimentally, the duty cycle can be used from: (i) Table 2 to assess exposure in an environment, (ii) Table 3 to assess theoretical maximal exposure, and (iii) Table 4 to assess exposure for different applications.

3.2 DUTY CYCLE FOR DIFFERENT WLAN APPLICATIONS

Figure 3 shows the duty cycle at 54 Mbps (channel occupation in %) versus time for three applications namely VoIP, video streaming, and file transfer. Transferring or downloading the file is the most "intensive application" (*D* around 60-69%). For the YouTube video streaming, the video file is buffered during the first 50 seconds (also around 60%) and after this period with high duty cycle, the channel occupation reduces to 0.1% because all data has been received and only basic control information is still being sent. Skype voice varies less with occupations around 1%. The measured average, 95th percentile, and maximal duty cycles *D* for the applications described above at 54 and 6 Mbps are summarized in Table 4. Clearly, the lowest data rate (6 Mbps) results in the highest duty cycles for all applications. Also the standard deviations are the highest for the lowest data rates. File transfer causes the highest duty cycles up to 66 % (54 Mbps) and 94% (6 Mbps), which approaches the theoretical maximal duty cycle of 69.83 % (54 Mbps) and 94.7% (6 Mbps) (see Section 2.3) and shows an excellent agreement between theoretical calculations and measurements. Thus, highest duty cycles *D* are obtained for file transfer (46% and 87% on average, p_{95} = 66% and 93% at maximum and minimum data rate, respectively). For maximum data rate (54 Mbps), this is followed by video applications; p_{95} = 65% for high quality video of 1080p while normal video of 360p and Skype video have 95th percentiles of about 2%, and voice applications (VoIP using Skype p_{95} = 1.3%). Audio streaming (using Spotify p_{95} = 0.2%, 54 Mbps) and surfing on the internet (here a news site, p_{95} = 1.3%, 54 Mbps) result in the lowest duty cycles. For minimum data rate (6 Mbps) analogue conclusions can be drawn.

This order of duty cycles was expected as the more “intensive” (such as downloading and video streaming) applications require more data to be transferred and thus result in a higher occupation of the Wi-Fi link. From the values of Table 4 it is clear that it is important to take realistic duty cycles into account as the average values are often below the theoretical maximum of Section 2.3. Also the standard deviations (SD) are listed to show the burstiness of the Wi-Fi traffic and the streaming protocol. These standard deviations vary from 0.5% (Skype voice) to 22% for 54 Mbps (YouTube video 1080p, see also Figure 3) and even from 1.4 to 31.1% for 6 Mbps. This burstiness is also shown by the high maximal values (e.g., average of 2% versus a maximal value of 66% for YouTube 360p at 54 Mbps, where three peaks for the duty cycle are measured and for the rest of time duty cycles below 1 % are obtained). The duty cycles of Khalid et al. (2011) cannot be compared with those of the applications provided here as the lessons in Khalid et al. (2011) consisted a mixture of audio and video streaming applications and file transfer.

Thus during intensive applications much higher duty cycles can occur and exposures can increase. One can use these duty cycles for realistic exposure estimations when activities of people are known well (e.g., exposure of children during video streaming in a class).

3.3 APPLICATION: SIMULATION OF FIELD STRENGTH WITH REALISTIC DUTY CYCLES

To investigate the impact of the resulting field strength with realistic duty cycles, we run simulations (Finite-Difference Time-Domain FDTD, SEMCAD-X, Speag, Switzerland) of a DLink DI-624 AirPlusXtremeG access point with an Equivalent Isotropically Radiated Power (EIRP) of 20 dBm. The considered frequency is 2.4 GHz. Simulations occur in free space and the antenna of the AP is modeled as a half-wavelength dipole. The maximum grid step does not exceed 0.07 times the wave length in free space. In FDTD calculations, the simulation domain is finite in extent and boundary conditions are applied. Uni-axial perfectly matched layers (UPML) are applied to the boundaries to avoid reflections back into the simulation domain. The number of layers is automatically set by the FDTD solver to obtain a selected efficiency of 99.9%. The padding or minimum distance between absorbing boundaries (UPML) and the bounding box around the human body model and the antenna was set to half a wavelength. These simulations are validated by measurements in an office environment (Plets et al. 2012), and good agreement is obtained. Fig. 4 shows the electric field strength as a function of the separation (up to 50 cm) from the access point and assuming D = 100 %. Also the ICNIRP reference level of 61 V/m for the general public is indicated (ICNIRP 1998).

At 30 cm from the AP (e.g., scenario of an AP on a desk in an office and using a high speed connection of 54 Mbps, which is realistic) and assuming a 100 % duty cycle, a field value of 5.53 V/m (11 times below ICNIRP) is obtained. But by applying a duty cycle of 1.4 % (overall median duty cycle in Table 2), 0.65 V/m (93 times below ICNIRP) is obtained. If we consider realistic high duty cycles in office environments and use the value of 6.1 % (p_{95} in office environments, Table 2), we obtain 1.36 V/m (45 times below ICNIRP). This gives an indication of the amount of overestimation of WLAN exposure when not applying realistic duty cycles: overestimations of a factor 5.53/0.65 = 8.5 and 5.53/1.36 = 4.1 are obtained for this example when comparing 100% duty cycles to overall median values and p_{95} values in offices, respectively. When assuming continuous video streaming at 54 Mbps (p_{95} = 65% for high definition video 1080p, Table 4), 4.44 V/m (14 times below ICNIRP) is obtained. This shows that it is important to take into account the duty cycle for WLAN when assessing exposure. The presented analysis enables more realistic estimates of WLAN exposure.

4 CONCLUSIONS

The WLAN duty cycle is determined experimentally in different environments at 179 locations in Belgium and the Netherlands using a spectrum analyzer in zero-span mode. The 50th percentile of the overall duty cycle equals 1.4 % and the 95th percentile is 10.4 % (SD = 6.4%). Largest duty cycles are observed in urban and industrial environments. Duty cycles are also experimentally assessed for various activities and applications. For lower physical data rates (lower modulation schemes) higher duty cycles will occur. Thus the worse the WLAN connection (when only lower modulations are possible), the higher the duty cycle and the resulting exposure can be. The theoretical upper limit for the actual 802.11a WLAN duty cycle is 69.8 % (maximum physical data rate of 54 Mbps) and 94.7% (minimum physical data rate of 6 Mbps). Excellent agreement between theoretical upper limits and worst-case measurements (most demanding applications) is obtained. File transfer over Wi-Fi results in highest duty cycles while surfing and audio streaming have median duty cycles lower than 3.2%. The duty cycles per environment and for the various applications can be used for practical exposure assessment where currently huge overestimations are made by assuming continuous WLAN exposure. For the application provided here, this overestimation ranged up to a factor 8 for the electric fields.

Future research will consist of realistic WLAN exposure assessment campaigns in different environments and applying the provided duty cycles. Also, environments such as schools and day-care centers could be considered in the future. Finally, we provided realistic worst-case duty cycles for the various activities. By accounting for usage patterns for these activities, actual averages could be obtained. The usage patterns might however be difficult to acquire in some cases (such as child behavior).

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List of captions

TABLE 1: Optimal SA settings for measuring correctly the duty cycle in a WLAN.

TABLE 2: Number of locations per environment and 50th and 95th percentile of the duty cycle in different environments.

TABLE 3: Calculated maximal duty cycle for different data rates for 802.11a and g.

TABLE 4: Measured average, 50th, 95th percentile, and maximum duty cycle for different activities at 54 and 6 Mbps.

Figure 1: 802.11 transmission protocol (ACK = acknowledgement, DIFS = Distributed Inter-Frame Space, SIFS = Short Interframe Space, B = backoff time, t = time).

Figure 2: Cumulative distribution function (cdf) of the duty-cycle D per environment (industrial, urban, suburban, and office, zoom-in from 0 to 20 %) measured at 179 locations spread over Belgium and the Netherlands.

Figure 3: Wi-Fi occupation during time for different activities at 54 Mbps (VoIP, video streaming, and file transfer).

Figure 4: Electric field of an access point at 2.4 GHz for different duty cycles (p_{50}, p_{90} office, video streaming).

Table

Parameter	**Value**
Span	0 MHz
Center frequency	Channel frequency: 2.4 GHz band
Detector	RMS
SWT (sweep time)	1 ms
RBW (resolution bandwidth)	1 MHz
VBW (video bandwidth)	10 MHz
Number of sweeps	2200

Table 1

Table

environment	number of locations	$p_{50}(D)$ (%)	$p_{95}(D)$ (%)	SD(D) (%)
Industrial	17	1.35	10.50	3.16
Rural	3	-	-	-
Suburban	30	1.18	4.55	7.37
Urban	82	1.43	11.05	7.14
Office	41	1.24	6.08	5.27
Residential	6	1.85	-	-
All evironments	179	1.36	10.44	6.35

-: not available, not enough values for accurate estimate; SD = standard deviation

Table 2

Table

Data rate (Mbps) 802.11a	6	9	12	18	24	36	48	54				
Duty cycle (%)[1] CW = 15	94.74	92.38	90.19	86.17	86.76	76.76	72.12	69.83				
Data rate (Mbps) 802.11g	**1**	**2**	**5.5**	**6**	**9**	**11**	**12**	**18**	**24**	**36**	**48**	**54**
Duty cycle (%)[1]	97.16	94.57	87.08	91.00	87.21	78.780	83.82	77.89	73.15	65.35	59.77	57.14

[1]for CSMA/CA: Carrier Sense Multiple Access/Collision Avoidance

Table 3

Table

application	PDR (Mbps)	avg(D) (%)	p_{50}(D) (%)	p_{95}(D) (%)	max(D) (%)	SD(D) (%)
Surfing news site	54	0.25	0.04	0.62	14.49	1.15
Skype voice	54	0.80	1.01	1.34	1.48	0.47
Skype video	54	1.08	1.41	2.02	3.65	0.78
Audio: Spotify	54	0.13	0.04	0.23	6.33	0.58
YouTube video 360p	54	2.35	0.07	2.14	65.56	11.55
YouTube video 1080p	54	10.69	0.07	64.53	66.23	22.22
File transfer	54	46.18	47.57	65.18	66.40	15.97
Surfing news site	6	1.57	0.33	2.89	89.37	7.46
Skype voice	6	3.10	3.18	4.52	11.05	1.35
Skype video	6	5.42	5.24	10.77	15.65	2.85
Audio: Spotify	6	6.70	0.17	91.15	92.84	23.18
YouTube video 360p	6	14.54	0.40	90.75	93.29	31.09
YouTube video 1080p	6	81.39	91.12	92.81	93.45	28.33
File transfer	6	87.41	91.46	93.14	93.58	17.81

PDR = physical data rate; D = duty cycle; avg = average duty cycle; SD = standard deviation

Table 4